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CALIFORNIA INSTITUTE OF TECHNOLOGY

BIG BEAR SOLAR OBSERVATORY

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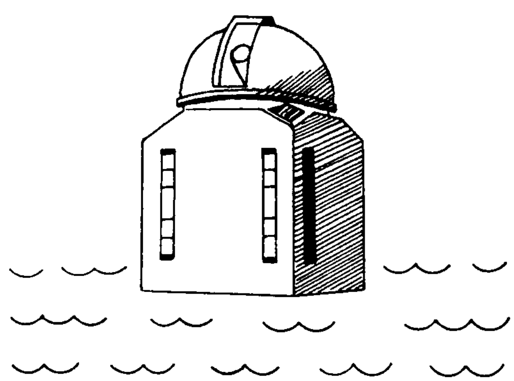

(NASA-CR-179736) THE SMALLEST OBSERVABLE ELEMENTS OF MAGNETIC FLUX (California Inst. of Tech.) 25 p

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THE SMALLEST OBSERVABLE ELEMENTS OF MAGNETIC FLUX

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ABSTRACT

We have determined the smallest detectable elements of magnetic flux by following elements in the process of cancellation with elements of opposite polarity. The last remaining visible segment of magnetic field of a cancelling feature can be used to infer the total magnetic flux and the possible size occupied by small flux elements. We used both photographic and digital videomagnetograms combining 4096 Zeeman frames made at Big Bear. Fifteen elements were measured near the vanishing point, in a 2-8 hour period. The minimum fluxes fall in the range of 1.0×10^{16} to 1.4×10^{17} maxwell, and the apparent size of these elements is in the range of 1 to 9 square arc seconds. A smooth decrease with no evidence of quantization in flux or size is observed. The smallest visible elements of network field, intra-network field, and ephemeral regions appear to be similar, suggesting that there is no generic difference between these fields. The present limit is still instrumental; elements smaller than 1×10^{16} would not have been detected. If the magnetic field strength has a magnitude of kilogauss, the real size of smallest visible elements is about 35 - 130 kilometers, and if the size is 300 km, the field strength is 15 - 200 gauss.

INTRODUCTION

Following the work of Stenflo (1975) and others there has been considerable interest in the smallest elements of magnetic field that might be found in the solar photosphere. In the quest for an orderly universe, it has been conjectured that there is a "basic magnetic element" out of which the observed flux elements are formed. Naturally this must refer to stable elements, since these elements must form and decay, and during that process be smaller than the "basic size". In his review of the characteristics of small scale magnetic field on the quiet Sun Harvey (1977) shows examples of the intra-network fields, estimating their flux at 5×10^{16} Maxwells. It is not clear if Harvey was looking for the smallest features; more likely he was referring to the typical intra-network fields. Simon and Zirker (1974) used spectroscopic observations to find minimum field strengths in the range 100 gauss to 1000 gauss, and sizes larger than 1.5" in the chromospheric network. These numbers correspond to 10^{18} Mx. Because of time and field limitations they could not really search for the "smallest elements". In the present work we have utilized time sequences to search for and measure flux elements at least ten times smaller, utilizing shrinking size to pick the smallest elements. The video technique has the advantage that (1) if we observe an element several times we know it is real and (2) if an element is shrinking or growing we have a hope of finding it even smaller than it is now.

The videomagnetograph at BBSO was built by Smithson and Leighton (Smithson, 1972). In 1979 it was rebuilt with a digital image processor, and in 1981 we improved the capability by installing RCA cameras with Nuvicon tubes, replacing the KDP crystal, and introducing computer programs permitting the accumulation of an almost unlimited number of frames. Introduction of a large storage disk permitted recording digital images, and the problem of calibration (using solar rotation Doppler images) has been worked out by Shi and Wang (1984). In practice up to 4096 frames are used, requiring 138 seconds. The long integration time only slightly degrades resolution, because there is an enhancement effect with superposition of many elements. Under good seeing conditions, the sensitivity of the system steadily increases with number of frames, and the noise level of the 4096 frame magnetogram is around 2 gauss. So although there is some distortion of strength and size, the total flux is still meaningful. Sequences of such sensitive long integration videomagnetograms show that the cancellation of magnetic flux occurs frequently on the quiet Sun (Martin 1983, Wang et al. 1984). As we follow the cancellation process, we can watch flux elements shrink and determine the smallest observable flux elements.

In this paper, we measure the magnetic flux of the last remaining visible segments of eight continuously shrinking magnetic features which appear continuously to cancel (by reconnection and subsidence, we assume) with other magnetic features of opposite polarity during periods of 2-8 hours. Although ephemeral regions, network, and intra-network regions show successively weaker fields, elements of the smallest size were found in each as the magnetic knots shrank. That this is not a question of changing VMG sensitivity is attested by the appearance of constant or growing flux in other magnetic elements, and calibration of digital magnetograms a few hours apart.

THE IDENTIFICATION OF SMALLEST VISIBLE FLUX ELEMENTS

Under excellent seeing conditions on 4 September 1983, 2048 and 4096 frame videomagnetograms of the quiet Sun were obtained at Big Bear Solar Observatory. Since a number of disk areas were being studied, the interval between frames for our area was typically 30 minutes. At 2251 UT and 0027 UT two series of digital magnetograms were recorded and calibrated. The calibration method has been described by Shi and Wang (1984), and is consistent within 5 - 20 %.

The photographic and digital magnetograms with 4096 frames at 0027 UT are shown in Figures 1 and 2. The numbers correspond to the elements enumerated in Table 1, and illustrated in the other figures. The curious appearance of the stronger fields is due to a wrap-around procedure which reverses the output sense when field strength fills the memory. Thus the successive brightness reversals are 1, 3, 5, etc. times the first level at which dark turns to bright or vice versa. We have compared our magnetograms with a Kitt Peak magnetogram taken earlier in the day and found them to match well.

The data permit us to detect 9 small ephemeral regions, which are marked by circles in Figure 1. We denote as ephemeral regions small dipoles more intense than the background fields which exhibit rapid growth in our sequences.

Figure 3 shows the time history of elements 1 and 2 in Figure 1. These are elements of magnetic field of sign opposite to the dominant local network which cancel with the larger network elements. Feature 1 is negative polarity near a positive polarity network feature which itself is anomalous in our field of generally negative network. It decreases steadily for more than 7 hours as it approaches the large network element of opposite polarity to its right; the residual feature still can be seen in the last frame. Feature 2 at the right is positive polarity and goes through the same process with an element of the dominant negative network. Since we did not see their early history we don't know their origin, but they probably are the remnants of ephemeral regions. Calibrated digital magnetograms of these two examples are plotted in Figure 4 and Figure 5 respectively. The right sides of these figures show an enlarged contour map of the smallest visible feature. The magnetic strength of each pixel has been plotted in about 0.5 arc sec intervals on the contour map. In the Figure 5 the residual feature is double on both the 2251 and 0027 frames, even though it is steadily decreasing.

In the last frame of Figure 3 we have enclosed within a circle a small ephemeral region which grows rapidly after 2155. Its growth shows that the disappearance of the elements in Table 1 is not an instrumental effect.

Figure 6 shows the evolution of element 5 in Figure 1, an example of cancellation involving ephemeral regions. Three small ephemeral regions emerged rather suddenly between the 1754 and 1935 frames. The strongest is marked by solid line, the other two, which are not well-defined, are marked by dashed lines. The positive pole of the strongest ephemeral region steadily decreases, apparently cancelling with a nearby negative fragment of network field and perhaps the other ephemeral regions. By the last frames only a tiny pole remained. The calibrated data are shown in Figure 7.

Other types of cancellation were also observed. The characteristics of all examples found on this day are given in Table 1. We adopt the following abbreviations: N -- network field, I -- intra-network field, E -- ephemeral region. In the last column we give the total flux of last and smallest visible features, using only pixels of magnetic field strength above 2.0 gauss. From the illustrated contours one can see that including points of weaker field will only slightly affect the total flux.

TABLE 1: EXAMPLES OF SMALLEST VISIBLE MAGNETIC FEATURES

NUMBER	TYPE OF FEATURE	CLASS OF CANCELLATION	TIME FOLLOWED	FLUX (10^{16} Mx)
1a	N	N - N	1625 - 0027	1.5
1b	N	N - N	1625 - 0027	1.3
2a	N	N - N	1625 - 0027	10.0
2b	N	N - N	1625 - 0027	1.7
3a	N	N - N	1625 - 0027	5.2
3b	N	N - N	1625 - 0027	2.8
3c	N	N - N	1625 - 0027	2.0
3d	N	N - N	1625 - 0027	2.4
4	N	N - N	1625 - 0027	13.6
5	E	E - N	1935 - 2251	13.0
6a	I	I - N	1935 - 0027	11.4
6b	I	I - N	1935 - 0027	1.3
7a	I	I - N	2155 - 0027	7.0
7b	I	I - N	2155 - 0027	4.8
8	UNKNOWN	UNKNOWN	1935 - 2251	4.5

We see that the smallest measured fluxes range from 1 to 14 x 10^{16} Maxwells, the average value being close to that mentioned by Harvey (1977). A number are in the 1-2 x 10^{16} range, an order of magnitude smaller than the "basic magnetic unit" discussed by Stenflo. Note that the size of the smallest features is roughly the same for all three classes, so network or ephemeral region features can be equally as small as intra-network.

DISCUSSION

In any deep magnetogram there are many small features which may or may not be real. Their reality can normally be determined by their successive appearance in several VMG's. We have restricted ourselves to features which can be followed as they shrank for 2 - 8 hours, so we are certain that they are real. Most of these smallest visible features are the residue of network elements and ephemeral regions. Most of the the smallest features on our magnetograms are elements of intra-network fields. but their lifetimes are short, about half a hour, and we do not have enough digital records in this run to trace their flux with certainty. However, we have a series of photographic videomagnetograms of interval 2 - 12 minutes just before the time of each digital record. These convince us that most of the intra-network features in Figure 1 and the contour map in Figure 2 are real and of the same minimum flux value. It is interesting to notice that the intra-network fields appear to be more abundant in some cells than in others. The typical value of the intra-network features would agree with Harvey's estimate.

Because the magnetograph is roughly linear, the total measured flux in an element is unaffected by seeing, except for threshhold effects. The measured element size is affected by the seeing, by telescope jitter during the long integration, and by the limited resolution of the Nuvicon camera used in these measurements. Each unit in Figure 2 corresponds to a pixel in our digital memory. Since the limiting resolution of the telescope is the order of 0.6 arc sec, one would expect the smallest features to be greater than an arc second, especially after averaging 2048 frames. In fact there are plenty of small features, and those discussed here appear to be 1-2 arc sec across. This suggests that they are well below the telescopic jitter which is about 1 arc sec rms.

Considering the all possible uncertainties and calibration errors, we estimate that the total flux values given are within a factor of 2 of the true value.

Because the fading is a gradual process it is hard to see how the elements can be made up of a small number of discrete flux tubes. Either they represent a continuum, or they are made up of a reasonably large number, at least the order of 10, of discrete elements. On the other hand it is clear that the magnetic elements do not fill the photosphere but make up isolated elements. The elements are simply much weaker than previously consider. We cannot say that the space between is field free.

The popular concept of elementary flux ropes is grounded on the obvious fine structure of the solar fields, and any magnetogram shows that the stronger fields are highly localized. But since these fields cannot live forever, they must at some time have been smaller, and we can safely predict they will be weaker again when they die out. The duration of these dying elements shows they are reasonably stable. Our data tells us nothing about the structure of the larger elements, only that they can shrink down to the smallest detectable size.

CONCLUSION

The smallest observable flux elements on the quiet Sun fall in the range of one to several times 10^{16} maxwell. Allowing for blurring, the field strength in these elements must be no more than a few tens of gauss, or if they contain a single intense field element, say 500 gauss, they must be smaller than 50 kilometers.

Since we have observed them to decay smoothly, they must contain a number of such elements, and probably are weaker still. The data are best reconciled to a continuum of magnetic features, rather than discrete elements.

No difference is found between the smallest detectable elements of network, intra-network, or ephemeral region field elements. The limitation is purely instrumental, and no doubt smaller elements could be detected by a more sensitive magnetograph. The difference in magnetic flux among different magnetic features measured depended only on the stage in the cancellation process.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1. BBSO 4096 frame videomagnetogram of a typical quiet region at 002720 UT, Sept. 5, 1983. The stronger magnetic features are characterized by the saturated rings which are due to a wrap-around procedure in frame addition and subtraction; the resulting contours are odd multiples of the first contour. The polarity of magnetic fields are indicated by the color of the outermost part of magnetic features (white positive, black negative). The seven disappearing in Table 1 are marked by number. Nine ephemeral active regions are circled.

Fig. 2. Calibrated digital videomagnetogram of the same field of view and at the same time as Fig. 1. The lowest contour is 5 gauss. The thicker line is positive polarity, the thinner line is negative polarity. The smallest visible magnetic features are indicated by the same number as in Fig. 1.

Fig. 3. The history of cancelling features 1 and 2, which are marked by open-ended rectangles and are labeled by 1 and 2. Feature 1 directly collides with a large positive network and continuously cancels with it. The mutual flux loss is revealed by losing the saturated rings and decreases in the area of both features. Feature 2 slides around a negative network and cancels with it. The smallest remaining features are marked by arrows. In contrast to the continuous decrease of flux of features 1 and 2, a small new ephemeral region emerged after 2155 UT and grew rapidly. It was enclosed within a circle.

Fig. 4. Contour map of cancelling feature 1 and its surroundings. A window around feature 1 is shown on the left side and the enlargement of it is on the right side. The cancellation process not only reduces the maximum magnetic field strength, but also reduces the area occupied by the cancelling magnetic features. This reveals that the mutual disappearance of magnetic flux is a real physical process, not a seeing effect. The distance between two pixels is less than 0.5 arc seconds.

Fig. 5. Contour map of cancelling feature 2 and its surroundings. The mutual flux loss is demonstrated by the reduction of the number of iso-gauss lines. The general pattern of feature 2 remained after the flux decrease.

Fig. 6. The evolution of cancelling feature 5. This feature is the positive pole of an ephemeral region which emerged after 1754 UT. It was continuously decreasing in size and strength while cancelling with negative network or other ephemeral region features. At 0027 UT this feature was reduced below the detectable limit, but its position was still marked in Fig. 1.

Fig. 7. The contour map of cancelling feature 5 and its surroundings at the last frame (2251) of Fig. 6.

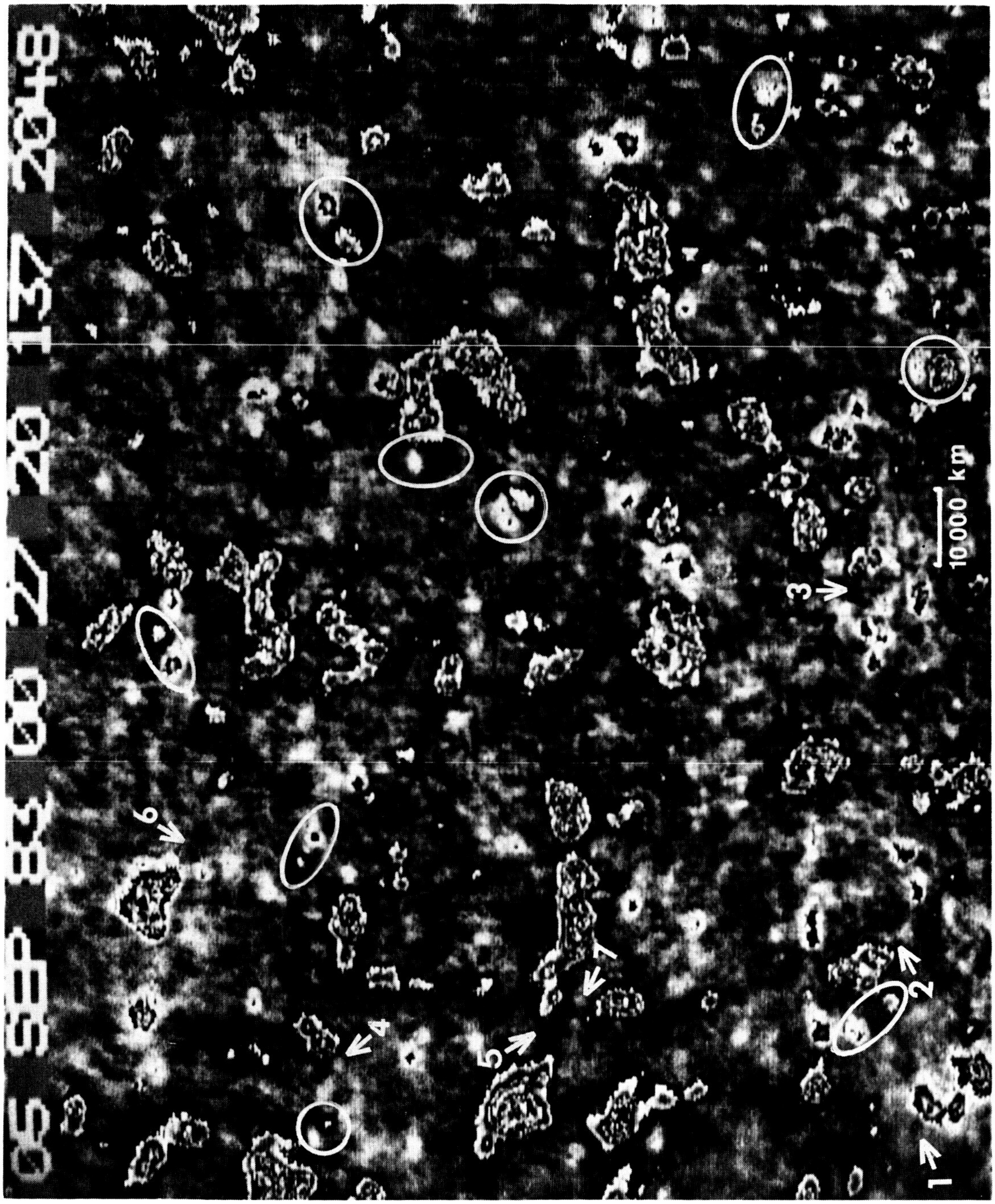


Figure 1

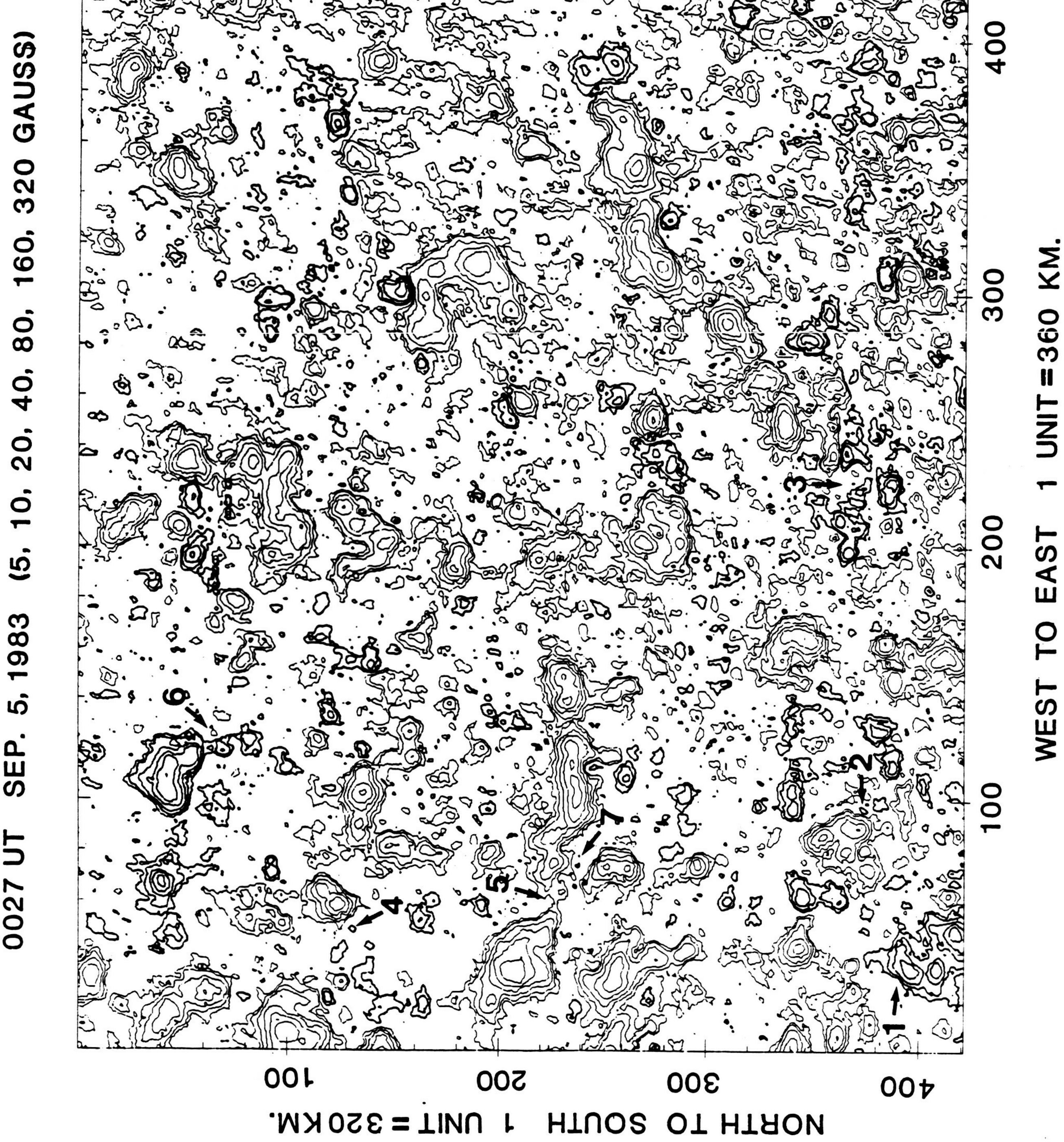

0027 UT SEP. 5, 1983 (5, 10, 20, 40, 80, 160, 320 GAUSS)
WEST TO EAST 1 UNIT = 360 KM.
NORTH TO SOUTH 1 UNIT = 320 KM.
100
200
300
400
1
2
3
4
5
6
7
8

Figure 2

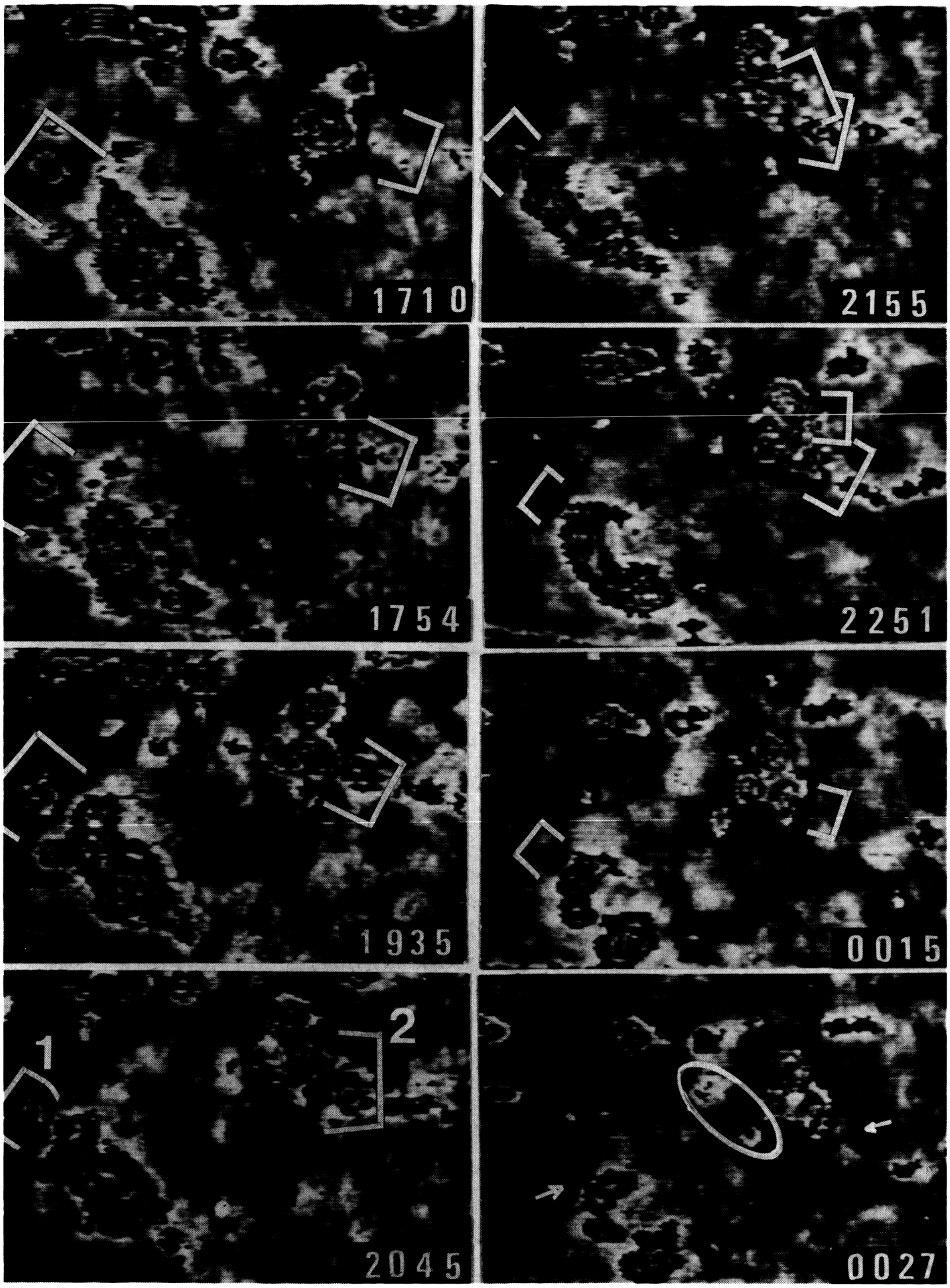


Figure 3

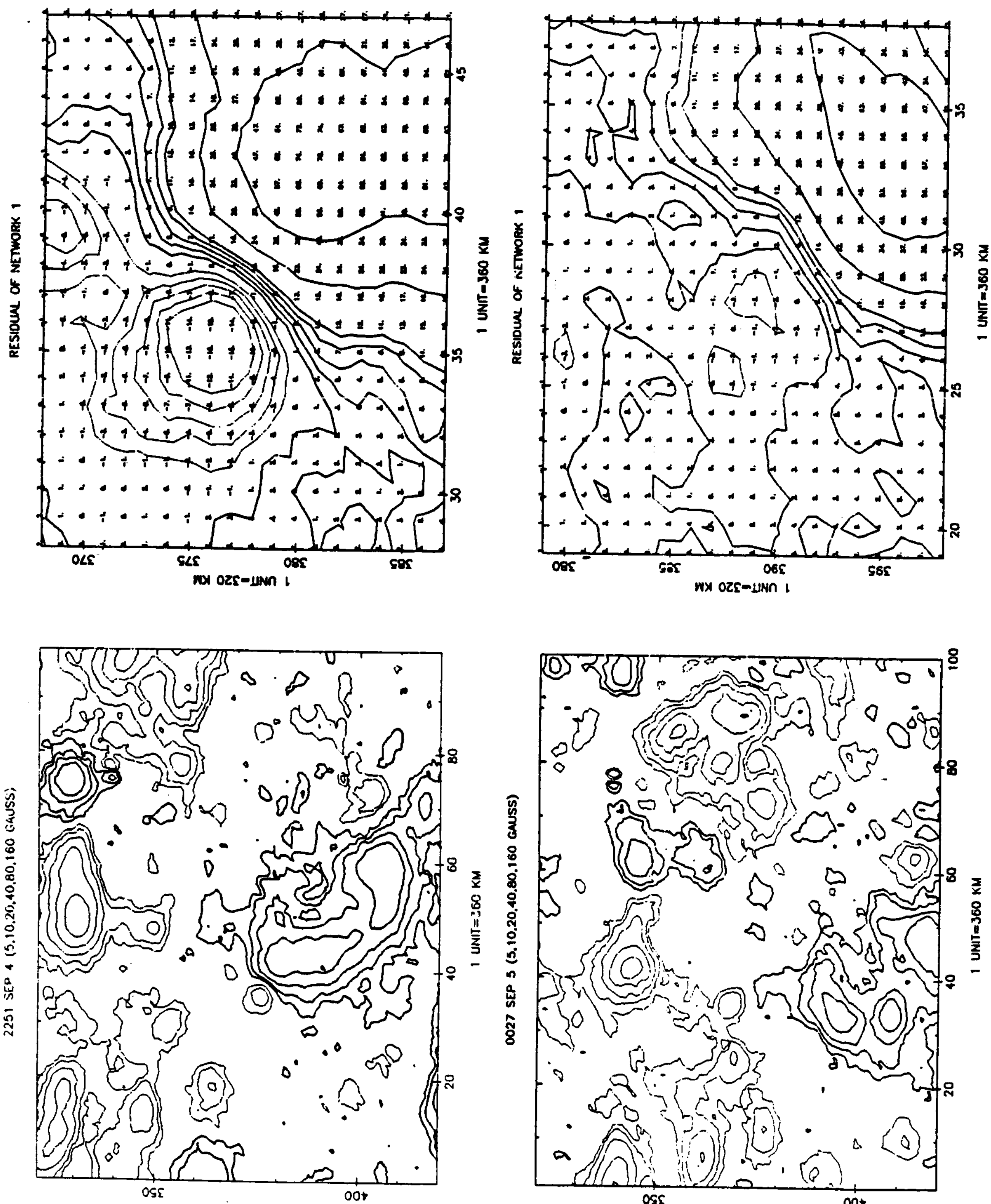
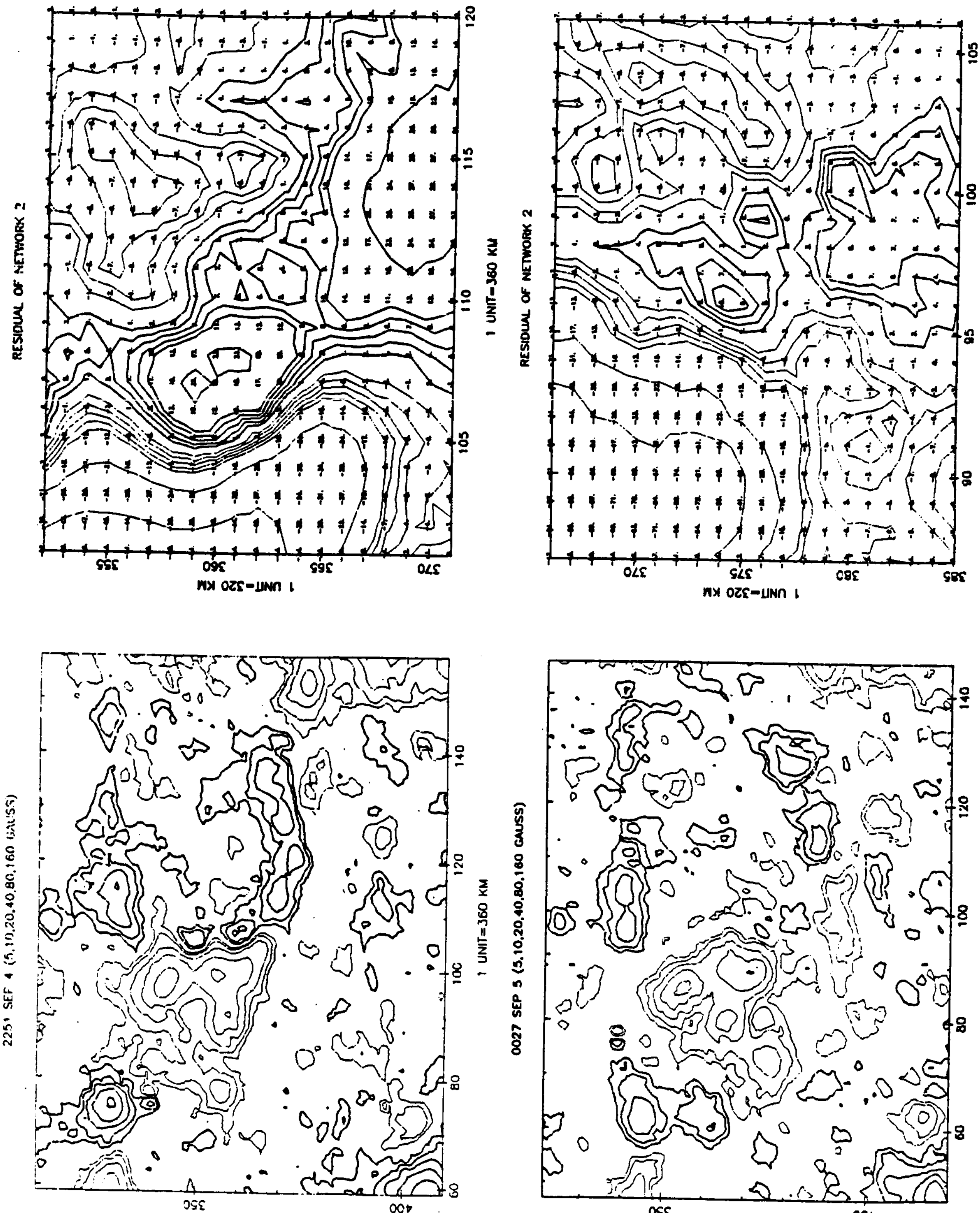

RESIDUAL OF NETWORK 1
1 UNIT=360 KM
1 UNIT=320 KM
RESIDUAL OF NETWORK 1
1 UNIT=360 KM
1 UNIT=320 KM
2251 SEP 4 (5,10,20,40,80,160 GAUSS)
1 UNIT=360 KM
1 UNIT=320 KM
0027 SEP 5 (5,10,20,40,80,160 GAUSS)
1 UNIT=360 KM
1 UNIT=320 KM

Figure 4


RESIDUAL OF NETWORK 2
1 UNIT=360 KM
1 UNIT=320 KM
RESIDUAL OF NETWORK 2
1 UNIT=360 KM
1 UNIT=320 KM
(5,10,20,40,80,160 GAUSS)
1 UNIT=360 KM
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0027 SEP 5 (5,10,20,40,80,160 GAUSS)
1 UNIT=360 KM
1 UNIT=320 KM

Figure 5

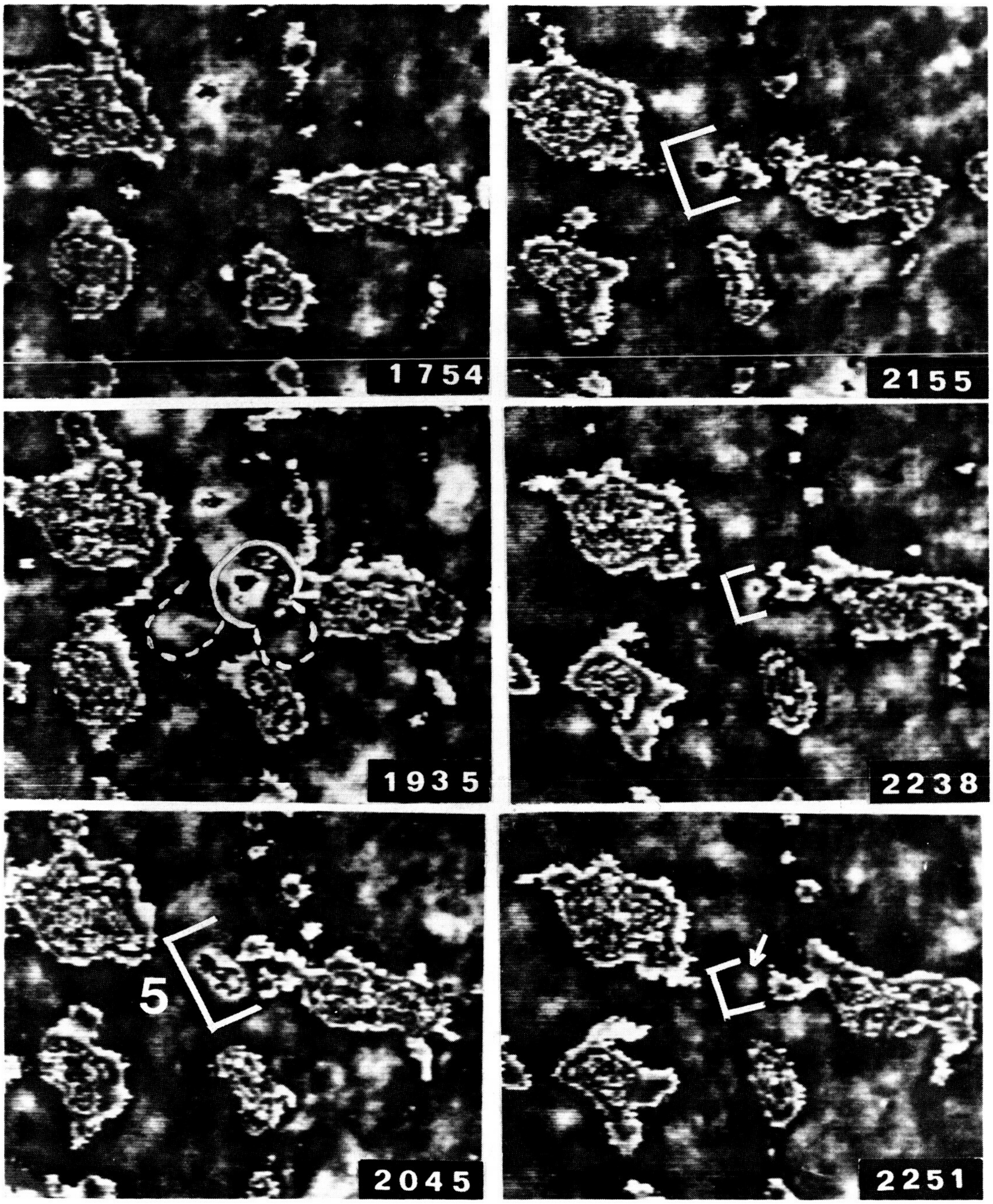
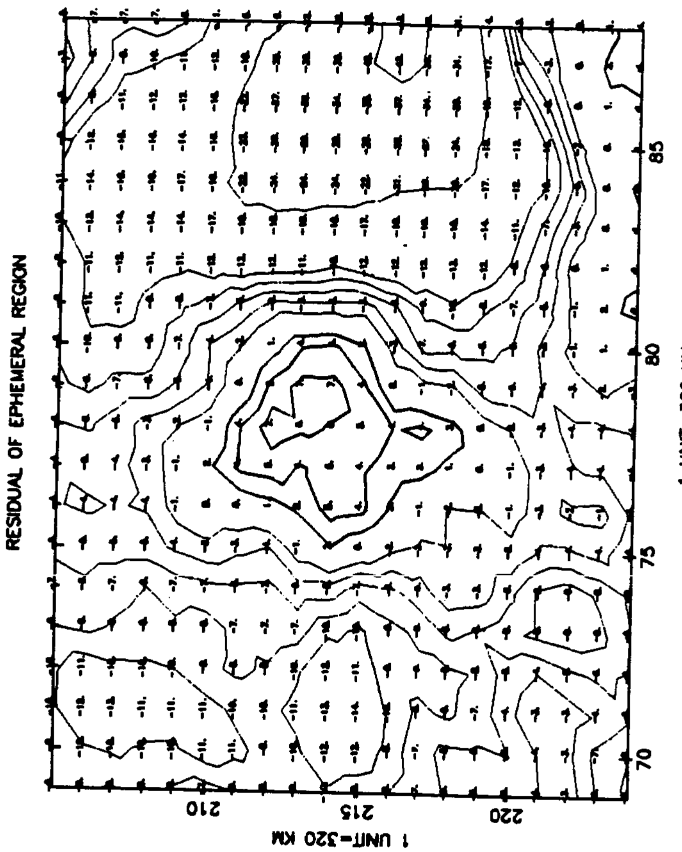


Figure 6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75
80
85
1 UNIT=320 KM
210
215
220

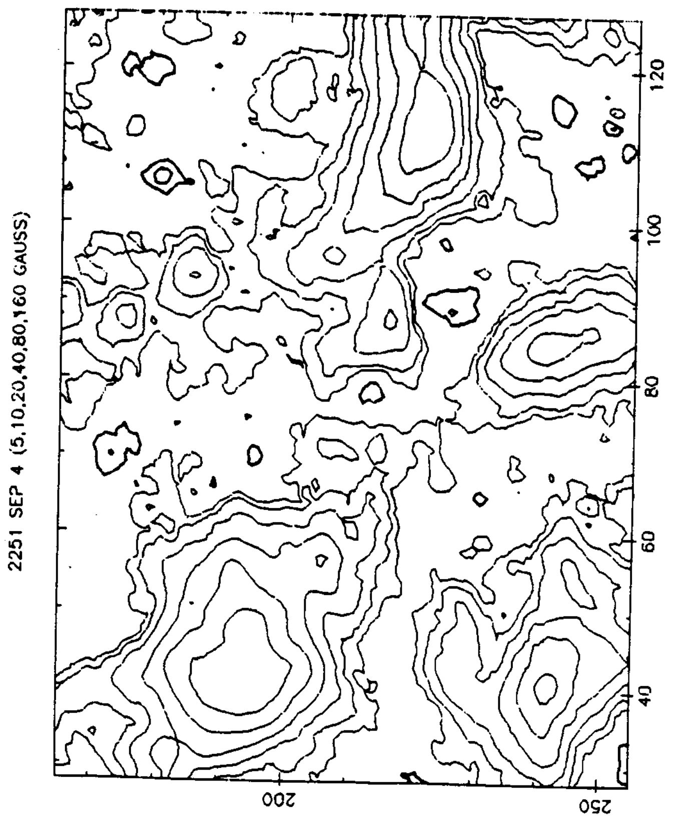
2251 SEP 4 (5,10,20,40,80,160 GAUSS)
1 UNIT=360 KM
40
60
80
100
120
200
250

Figure 7